# Detection of Extra-solar Planets around Radio-emitting Stars by VLBI Astrometry

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**Abstract.**
**A planet orbiting a radio-emitting star can be indirectly detected by high-precision Very Long Baseline Interferometry (VLBI) astrometry through the reflex orbit of the star. We have observed the radio-emitting star $\sigma^2$CrB at 12 epochs over 7 years by VLBI and fitted its 5 astrometric parameters to the measured coordinates. The post-fit coordinate residuals have an rms scatter of 0.31 mas (mill iarcseconds) if all observations have the same weight. However, the variability of the radio flux density of $\sigma^2$CrB led us to split the data into two subsets including 7 low-flux density epochs (S < 7 mJy) associated with the quiescence level and 5 high-flux density epochs (S >10 mJy) associated with outbursts. Interestingly, the rms of the post-fit coordinate residuals are 0.20 mas for the 7 quiescent epochs and 0.36 mas for the 5 active epochs. These rms are comparable to the full displacement of 0.20 mas that would be caused by a Jupiter mass around $\sigma^2$CrB.**

**The SNR-limited astrometric precision of such VLBI observations is 10 microarcsecond, i.e. 20 times better than this displacement. The likely primary source of the present systematic are the time-varying structure of the phase reference extragalactic radio source 1611+ 343 used to integrate enough VLBI data to detect the weak radio star. This effect will be corrected in future observations.**

**Key words:** VLBI astrometry, radio stars, extra-solar planets

## 1 Introduction

Astrometric monitoring of the minute displacement of a star around the barycenter of a system that possibly includes planetary companions has been an indirect method for detection of extra-solar planets for several decades at optical wavelength (van de Kamp and Lippincott 1951). The motion of a single planet in a circular orbit around a star causes the star to undergo a reflex circular motion around the star-planet barycenter. When projected on the sky, the orbit of the star appears as an ellipse with angular semimajor axis $\theta$ given try :

$$\theta = \frac{m_p}{M_*}\frac{a}{d} \qquad (1)$$

where $\theta$ is in arcsec when the semimajor axis a is in AU, the mass of the planet ($m_p$) and the mass of the star ($M_*$) are in solar masses and the distance $d$ is in pc. For example, observing the solar system from a distance of 10 PC, the presence of Jupiter would be revealed as a periodic circular displacement in the Sun's position, with an amplitude $\theta$ of 0.5 milliarcsecond (mas) and a period of 11.9 years. More generally, the astrometric accuracy required to detect giant planets is in the submilliarcsecond range, except for very nearby stars where it can reach several milliarcseconds.

Technical advances in Very Long Baseline Interferometry (VLBI) with the Mark III recording system (Rogers et al 1983) have provided sufficient sensitivity to detect reliably radio-emitting stars over the last few years. We have carried out VLBI measurements of the position of the radio star $\sigma^2$ CrB since 1987 and demonstrated submilliarcsecond astrometric precision during 7 years.

## 2 Phase referenced VLBI technique for high-precision astrometry of weak radio objects

VLBI is an astronomical technique using an array of antennas (two or more) separated by baselines of a few thousands of kilometers which simultaneously observed the same radio source to record its continuum signal over a limited bandwidth, typically a few tens of MHz, on video magnetic tapes. For each pair of antennas, the recorded signals are later cross-correlated on a specialized processor. The coherence of the cross-correlated radio signal is usually no more than 10-15 minutes. When a radio source is so weak that it cannot be detected within this duration, one has to resort to the phase-referencing VLBI technique which allows many hours of VLBI observations to be combined in a single coherent integration period. The radio-emitting stars are about 100-1000 times weaker than quasars usually detected by VLBI in a few minutes of integration and so we had to resort to multi-hour integration for our project. For this technique, a reference for the VLBI phase must be established by observing an angularly nearby strong extragalactic source alternately with the weak program source with a cycle time of a few minutes. This approach allows also high-accuracy differential astrometry because the prime observable used is the VLBI phase. Hence, relative position between the weak radio source and reference extragalactic source can be measured precisely to a small fraction of the interferometer fringe spacing ($\sim 1$ mas). The phase-referencing VLBI technique as applied in our VLBI astrometric program *is* described in detail in Lestrade *et al* (1990).

## 3 Results of a series of VLBI observations of the star $\sigma^2$ CrB :

$\sigma^2$ CrB is an RS CVn close binary whose orbital motion has a period of 1.1 day and a separation of 1.2 mas (major-axis). Phase-referenced VLBI observations of $\sigma^2$ CrB were conducted at 12 epochs between May 1987 and November 1994. Observation dates, flux densities and orbital phases are in Table 1. At 5 GHz, our program used the VLBI array made of the following antennas: the Phased-VLA (NRAO, NM), Bonn (MPI, Germany), Medicina (Bologna, Italy), Greenbank (NRAO, WVa), Haystack (MIT, Mass), OVRO (Caltech, CA) and, at 8.4 GHz, the VLBI array was made of Goldstone (DSN, CA), Hat Creek (Berkeley, CA), VLA (NRAO, NM), OVRO (Caltech, CA), Haystack (MIT, Mass) and newly commissioned VLBA radiotelescopes (USA). 'J'he total data integration times were between 5 and 8 hours at each epoch. The VLBI data acquisition system was the Mark III system (Rogers et al. 1983) used in a mode to record a bandwidth of 28 MHz. The corresponding detection threshold is about 2 milliJansky (1 OC-J). All the cross-correlation of the recorded signals was carried out at the Mark 111 Processor at Haystack Observatory (MIT, Mass) (Whitney 1988).

| Obser. Date | Orbital phase (cycle) | Frequency (GHz) | Flux density ( mJy ) |
|---|---|---|---|
| 87/05/26 04 UT | 0.56 | 5.0 | 10 |
| 88/11 /16 17 UT | 0.93 | 5.0 | 28 |
| 89/04/13 06 UT | 0.25 | 5.0 | 7 |
| 90/11/16 23 UT | 0.37 | 5.0 | 3.8 |
| 91/04/12 10 UT | 0.86 | 8.4 | 19.5 |
| 92/01/15 13 UT | 0.88 | 8.4 | 4.6 |
| 92/06/08 04 UT | 0.89 | 5.0 | 13 |
| 92/08/03 05 UT | 0.06 | 8.4 | 3.4 |
| 93/03/11 07 UT | 0.14 | 8.4 | 8 |
| 93/10/02 19 UT | 0.44 | 8.4 | 3.7 |
| 94/03/25 13 UT | 0.88 | 8.4 | 6 |
| 94/11/23 12 UT | 0.04 | 8.4 | 4 |

Table 1: VLBI observations of $\sigma^2$ CrB at 12 epochs.

The 5 astrometric parameters of $\sigma^2$ CrB (2 coordinates, 2 proper motion components and parallax) were estimated by a least square fit with the 24 coordinates measured at the 12 epochs. Figure 1 shows the results of the fit and the post-fit residuals. The uncertainties of all the measured VLBI coordinates were set to 0.31 milli-arcsec to make the reduced-$X^2$ close to unity for the number of degree of freedom 19 in the fit. The rms of the post-fit coordinates residuals is 0.31 mas. With such an adjustment, the formal uncertainties for the 5 fitted parameters are 0.12 mas for the relative position between $\sigma^2$ CrB and the reference source 1611+343, 0.05 mas/year for the proper motion and 0.10 mas for the trigonometric parallax. The correlation matrix indicates that the 5 parameters are well separated.

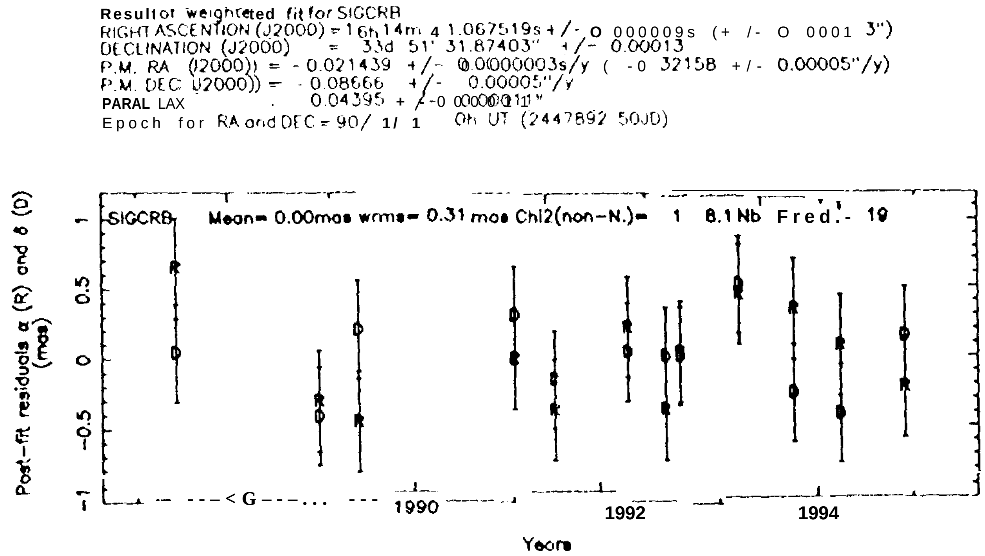


Figure 1 : Result of the fit of the 5 astrometric parameters of $\sigma^2$ CrB adjusted to its coordinates measured by VLBI at 12 epochs.

## 4 Implications for the presence of planets around the radio star $\sigma^2$CrB

The post-fit coordinate residuals of $\sigma^2$CrB in Figure 1 have an rms scatter of 0.31 milliarcseconds if all observations have the same weight in the fit. However, the variability of the radio flux density of $\sigma^2$CrB led us to split the data into two subsets including 7 low-flux density epochs (S < 7 mJy) associated with radio quiescence and 5 high-flux density epochs (S > 10 mJy) associated with radio outbursts of the star. interestingly, the rms of the post-fit coordinate residuals are 0.20 mas for the 7 quiescent epochs and 0.36 rnas for the 5 active epochs.

It is interesting to study the accuracy necessary to detect the presence of planets around $\sigma^2$CrB. The log-log representation of eq (1) with the parameters $m_p = 1$ Jupiter mass, $M_* = 2.26\ M_\odot$ and d = 22.7 pc for $\sigma^2$CrB is in Figure 2 and the total planetary reflex displacement is 26' = 0.20mas. The diagonal line of constant astrometric signature follows eq (1 ) for $2\theta = 0.20$mas and all points above this line represents larger planetary perturbations, We assume that a full orbital period of the planet must be sampled during the total span of observations to separate the sinusoidal planetary signature from the fitted linear proper motion. In these conditions, the maximum semimajor axis a of a planet corresponds to the total observation span through the third Kepler law. This upper limit on

$a$ is 5.0 AU for our 7.5 years of observations and is the vertical dashed line in Figure 2. The shaded area indicates the parameter space (u, $m_p$) that are excluded by observations for a possible planet. Interestingly, the present post-fit rms (0.20 mas) of our VLBI measurements at the radio quiescent epochs corresponds exactly to the total displacement expected for the detection threshold of a Jupiter-like planet around $\sigma^2$ CrB when 12 years of data are collected. This conclusion is consistent with our previous report with 8 epochs of observations in Lestrade *et al* (1994).

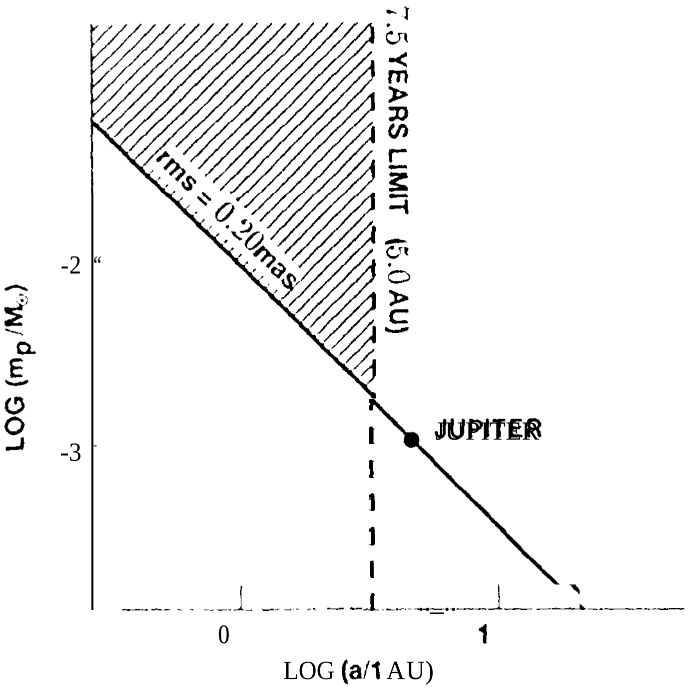


Figure 2: Log-Log representation of eq (1) for the rms of the post-fit coordinate residuals of $\sigma^2$ CrB. The shaded area is the parameter space (semimajor axis $a$, mass $m_p$) that are excluded by VLBI astrometric observations for a planet around this star. The detection of a Jupiter mass around $\sigma^2$ CrB required an astrometric accuracy of 0.20 mas.

## 5 Final remarks

We have demonstrated that phase-referenced VLBI observation of the radio star $\sigma^2$ CrB can achieve an astrometric precision of 0.20 mas. Interestingly, this precision is close to the level of perturbation around the linear proper motion of the star expected if a Jupiter-like planet is in orbit around it. At present, there are about 30 radio stars that could be monitored for a planetary search program by astrometric VLBI observations. But the scarcity of VLBI observing time has made such a program unpractical till now. However, the new VLBA of NRAO in USA and EVN/JIVE in Europe should make it possible in the near future. In addition, forseen technical improvements to enhance the sensitivity of the recording system by the end of the decade should lengthen the list to about 60 candidate stars.

The location of the radio centroid within a spectroscopic binary, such as $\sigma^2$ CrB, is a crucial question. If the radio emission is associated with only one of the stars, then a total displacement of 1.2 mas correlated with the orbital phase of the system should be seen in our coordinates residuals since the observations were taken at various orbital phase of the spectroscopic system (see Table 1). A precise ephemeris of orbital phase has been established for $\sigma^2$CrB by Bakes (1984). The post-fit residuals with positions measured at radio quiescent epochs do not seem to be dominated by this orbital motion but it might be the case during outbursts and we need additional observations to cover more uniformly the whole orbit. There is no theoretical model of the radio emitting region that can be used to set a limit on the stability of the radio centroid. It must be determined observationally and the rms of our post-fit coordinate residuals (0.20 mas or 1 $R_\odot$ at $\sigma^2$ CrB) can also be interpreted as a measure of this stability.

The theoretical precision for an interferometer is $\sigma_{\alpha,\delta} = \frac{1}{2\pi}\frac{1}{SNR}\frac{\lambda}{B}$ (Thompson, Moran, Swenson 1986) and for our observations, $\sigma_{\alpha,\delta}$ is 10 microarcseconds with $B = 3000$ km, $\lambda = 3.6$ cm and SNR > 15. Hence, the astrometric precision achieved for $\sigma^2$ CrB is not SNR-limited (Signal-to-Noise-Ratio-limited). Presently, there are at least three systematic error sources that prevent reaching this ultimate precision of the observations: 1) the extrapolation of the reference source VLBI phase in switched observations to the time of the star observation, 2) the differential contribution of the atmosphere and ionosphere along the two lines of sight to the reference source and target star and 3) the structures of the reference source and, possibly, of the star. We are taking steps to address these questions.

Table 2 summarises the relevant information for the 11 radio-emitting stars of our Hipparcos astrometric program (Lestrade *et al* 1992) in order to compute the total sky displacement 2 x $\theta$ from eq 1 expected for a Jupiter-like planet around these stars. The values calculated for 2 x $\theta$ in this Table compare favorably to the potential SNR-limited astrometric precision of phase-referenced VLBI observations on intercontinental baselines. Hubble 4 and HDE 283572 of the Taurus-Auriga dark clouds in Table 2 are Pre-Main-Sequence stars that are not part of our current program but have been detected already on intercontinental VLBI baselines by Phillips, Lonsdale and Feigelson, 1991. These two stars were part of a survey at 1.3 millimeter and were not detected while others stars of the cloud were detected. The detections were interpreted as evidence for a dust-disc around the stars, i.e. protoplanetary material (Beckwith et al 1990). One can speculate that Hubble 4 and HDE283572 are more evolved and, possibly, that their initial dust-disc have already collapsed into planets. It is also noticeable that UV Ceti, the nearest radio emitting star, would exhibit perturbations by an Earth-mass planet whose magnitude (8 $\mu$arcseconds) is comparable to the theoretical VLBI astrometric precision of 10 $\mu$arcseconds.

| Star | Class | Distance (pc) | Masses (M.,),) | hot/cool Sp. Type | $\theta_{Jupiter}$ ($\mu$as) | $\theta_{Earth}$ (pas) |
|---|---|---|---|---|---|---|
| 1.S1 61303 | X-ray | 2000 | | | | |
| Algol | Algol | 27 | 3.6/0.79 | K0IV/B8V | 40 | |
| UXARI | RS CVn | 50 | > 0.63/ >0.71 | G5V/K0IV | < 80 | |
| IIR1099 | RS CVn | 36 | 1.1/1.4 | G5IV/K1IV | 50 | |
| HDE 283447 | PMS (WTT) | 160 | 1.74 | K3 | 18 | |
| I1R511O | RS CVn | 53 | 1.5/0.8 | F2V/G0IV | 40 | |
| $\sigma^2$ CrB | Rs CVn | 21 | 1.12/1.14 | F6V/G0V | 100 | |
| Cyg x 1 | X-ray | 2000 | | | < 10 | |
| HD 199178 | FK Corn | 140-90 | 3.2 ? | G5 III-IV | > 10 | |
| AR Lac | RS CVn | 47 | > 1.3/ >1.3 | G2IV/K0IV | 40 | |
| IM Peg | RS CVn | 50 | 4 ? | K2III-II | 10 | |
| Hubble 4 | PMS (WTT) | 160 | 0.5 -2.0 | K7 | > 15 | |
| HDE283572 | PMS (WTT) | 160 | 0.5 -2.0 | G5 | > 15 | |
| EV Lac | dMe | 6 ? | 0.3 | | 2700 | |
| UV Ceti | dMe | 2.7 | 0.3 | | 12000 | 8 |
| 47 Cas | MS | 38 | 1.0 | F0V | 150 | |
| YZ Cmi | dMe | 6.0 | 0.3 | | 2700 | |
| EQ PegA/B | dMe | 6.4 | 0.3-{ 0.3 | | 3500 | |
| $\chi^1$ Ori | GOV | 10 | 1.0 | | 600 | |
| Wolf 630 AB | dMe | 6.2 | 0.3+( 0.3 ?) | | 1800 | |
| AT Mic | dMe | 8.8 | 0.3-1 (0.3 ?) | | 1200 | |
| AU Mic | | 8.8 | 0.3 | M0e | 1800 | |
| HD16157 | dKe | 11.4 | 0.3 | dK7e | 2000 | |
| HD283750 | dke | 16.7 | 0.3 | dK5e | 1500 | |

Table 2 : The 11 radio-emitting stars of our VLBI program and the relevant information to compute the total sky displacement 2 x $\theta$ for a Jupiter-like planet around them.

## 6 Acknowledgements

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